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EVIDENCE FOR CIRCUMSTELLAR DISKS AROUND YOUNG BROWN DWARFS IN THE TRAPEZIUM CLUSTER

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ABSTRACT

We report the results of deep infrared observations of brown dwarf candidates in the Trapezium cluster in Orion. Analysis of the JHK color-color diagram indicates that a large fraction ($\sim$ 65% $\pm$ 15%) of the observed sources exhibit infrared excess emission. This suggests the extreme youth of these objects and in turn, provides strong independent confirmation of the existence of a large population of substellar objects in the cluster. Moreover, this suggests that the majority of these substellar objects are presently surrounded by circumstellar disks similar to the situation for the stellar population of the cluster. This evidence for a high initial disk frequency ($>$ 50 %) around cluster members of all masses combined with the smooth continuity of the cluster's initial mass function across the hydrogen burning limit suggests that a single physical mechanism is likely responsible for producing the entire cluster mass spectrum down to near the deuterium burning limit. The results may also indicate that even substellar objects are capable of forming with systems of planetary companions.

Subject headings: circumstellar matter — infrared: stars — open clusters and associations: individual (Trapezium Cluster) — stars: low-mass, brown dwarfs — stars: pre-main sequence

1. INTRODUCTION

Among the most fundamental issues raised by the existence of brown dwarfs is the question of their origin and genetic relationship to planets and stars. Are brown dwarfs giant planets or small, failed stars, or, something else altogether different? The critical test needed to resolve this question is to determine whether brown dwarfs primarily form within circumstellar disks as companions to stars, similar to planets, or from their own individual cloud cores or fragments, like stars. To date, the most important observations bearing on this question have been: 1) the observed lack of close brown dwarf companions found in radial velocity surveys of nearby field stars (the so-called brown dwarf desert, e.g., Marcy & Butler 1998) and 2) the existence of free floating brown dwarfs in young clusters (e.g., Bouvier et al. 1998). Both facts would appear to implicate a stellar (non-planet like) origin for these objects, i.e., formation from independent, contracting fragments of the parental molecular cloud. However, our understanding of the origin of substellar objects is far from complete. For example, an alternative formation scenario has been recently proposed by Reipurth & Clarke (2001) who suggest that most freely floating brown dwarfs did not form from their own protostellar fragments, but instead were initially formed as companions to other protostars and then were dynamically ejected via 3 body encounters before they could grow into stellar mass objects.

The most direct way to address the question of the origin and nature of brown dwarfs is to investigate the properties of extremely young substellar objects in regions of active star and planet formation. For example, finding young brown dwarfs surrounded by their own circumstellar accretion disks would likely implicate a stellar-like formation mechanism (from individual cloud fragments) and place strong constraints for the theoretical models of their origin (e.g., Reipurth & Clarke 2001). Moreover, such a finding would raise the interesting question of whether planetary companions can form around such objects.

Recently, Lada et al. (2000) used near-infrared ($1-3\,\mu$m) color-color diagrams to show that a large fraction ($\sim 80-85$%) of the stars in the young Trapezium Cluster display thermal infrared excess indicative of circumstellar disks. Further, they found that the fraction of stars with disks remained high with decreasing mass to near the hydrogen burning limit. Below this limit, their observations became incomplete. Does the incidence of circumstellar disks also continuously extend across the hydrogen burning limit to substellar mass objects?

Deeper infrared observations reveal a substantial population of faint sources which could be free floating substellar objects in this cluster (McCaughrean et al. 1995; Muench, Lada, & Lada 2000; Lucas & Roche 2000; Hillenbrand & Carpenter 2000; Luhman et al. 2000). However, the identifications of these sources as substellar objects are not secure because observations of nearby unextincted control fields reveal significant numbers of field stars in the corresponding brightness range (Muench et al. 2001), suggesting that field star contamination could be a severe problem, especially for the faintest candidates. Reasonable attempts to account for the effects of the screen of extinction provided by the molecular cloud behind the Trapezium do suggest that the vast majority of the brown dwarf candidates are not reddened field stars (Hillenbrand & Carpenter 2000; Muench et al. 2001). However, independent confirmation of membership is clearly important and could be provided by indications of extreme youth, such as the presence of infrared excess and dusty disks surrounding these objects.

In this letter, we present an observational analysis of a deeper and more complete set of near-infrared observations for the candidate brown dwarf population in the Trapezium Cluster. We find a relatively large fraction of the candidates exhibit infrared

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excess indicative of circumstellar disks. This confirms both their membership in the cluster and their status as substellar objects and perhaps suggests an origin for them that is more stellar-like than planetary-like.

2. OBSERVATIONS

We obtained deep JHK$_S$ images of the central $5' \times 5'$ region of the Trapezium Cluster during 1 hour on 14 March 2000 using the SOFI infrared camera on the ESO 3.5 m New Technology Telescope in La Silla, Chile. The NTT telescope uses an active optics platform to achieve ambient seeing and high image quality and the SOFI camera employs a large format 1024×1024 pixel Hawaii HgCdTe array. We configured SOFI to have a $4'.95 \times 4'.95$ field of view with a plate scale of $0''.29$ /pixel. Seeing conditions were superb ($\sim 0.55''$) and our 90% completeness limit is estimated at K$_S$ $\sim$ 17.5. These NTT observations were obtained as part of larger program to catalog the infrared JHKL magnitudes of sources over the entire mass spectrum in the Trapezium Cluster. The brighter portion of this catalog was presented in Lada et al. (2000), and only the NTT observations are discussed in this paper. A complete description and analysis of these observations is presented in the forthcoming Muench et al. (2001, hereafter MLLA2001).

3. RESULTS AND ANALYSIS

In figure 1 we construct the infrared color-magnitude diagrams for those NTT Trapezium sources which were simultaneously detected at JHK$_S$ wavelengths. In these diagrams, we compare the locations of these sources to the location of the theoretical isochrone from the Baraffe et al. (1998, hereafter BCAH98) non-grey evolutionary models at the assumed mean age (1 Myrs) and distance (400 pc) of this cluster. The BCAH98 theoretical isochrone closely follows the near-IR colors of the Trapezium sources, forming an excellent left-hand boundary to the source distribution in this color-magnitude space. The Trapezium sources are reddened away from this boundary with implied extinctions of A$_V$ $\sim 1-35$ mag.

We identified candidate brown dwarfs in the Trapezium Cluster by comparing the infrared luminosities of detected sources to those predicted by the theoretical evolutionary models. We selected all the NTT sources in the J-H/H diagram (figure 1a) fainter than the predicted luminosity of the hydrogen burning limit (hereafter HBL; 0.08 M$_\odot$)[6] but brighter than the luminosity of an 0.02 M$_\odot$ object. This lower limit was chosen because the current theoretical evolutionary models do not extend much below this mass, and because we wish to exclude cooler, lower mass objects whose intrinsic colors are not well constrained. Between these two mass/luminosity limits, we identified 112 candidate brown dwarfs in the J-H/H diagram. We also indicate in Figure 1 the locations of 10 Trapezium Cluster members with spectral types equal to or later than M6 in Hillenbrand (1997). The spectral type M6 is an important boundary because recent spectroscopic studies have suggested that it represents the hydrogen burning limit in very young ($\tau \lesssim 10$ Myrs) clusters (Luhman 1999). In figure 1a, these late type sources are on average 1 magnitude brighter than our adopted hydrogen burning limit. The faintness of our IR selected brown dwarfs relative to these late type sources confirms that we are likely selecting sources below the HBL.

We refine our selection of brown dwarf candidates by plotting the J-H/H candidates in the H-K$_S$/K$_S$ color-magnitude diagram in figure 1b. In this diagram a number of candidates are brighter and redder than the hydrogen burning limit. We retain these as likely brown dwarf candidates because they have photometric errors which are much too small to have scattered them to this location, because they are fainter than most of the M6+ dwarfs, and because excess 2 μm flux from circumstellar disks could act to brighten and redden such sources out of the brown dwarf regime in the H-K$_S$/K$_S$ color-magnitude diagram. A few very faint candidates scatter below the 0.02 M$_\odot$ limit in the H-K$_S$/K$_S$ diagram, and we exclude these sources from our final sample.

In figure 2, we plot the H-K$_S$/J-H color-color diagram for the 109 candidate brown dwarfs. We also plot for comparison the loci of colors for giants and for main-sequence dwarfs from Bessell & Brett (1988). We extended the loci of M dwarf colors in figure 2 from M6 to M9 using the empirical brown dwarf colors compiled in Kirkpatrick et al. (2000). The predicted effective temperatures of 1 Myr brown dwarfs from the BCAH98 evolutionary models are quite warm, e.g. T$_{eff}$ $\geq$ 2500K for masses greater than our 0.02 M$_\odot$ limit. Therefore, we expect that the intrinsic infrared colors of such young brown dwarfs are no redder than those of M9 dwarfs (J-H = 0.72; H-K$_S$ = 0.46 Kirkpatrick et al. 2000) which agree well with the H-K colors predicted by current model atmospheres of low surface gravity, 2600K sources (Allard et al. 2001)[7].

We find 65% $\pm$ 15% (71/109) of our candidates fall to the right of the reddening band for M dwarfs and into the infrared excess region of the color-color diagram. We further determine that 54% of the candidates have an infrared excess that is greater than their 1σ photometric uncertainties in color. In addition to normal photometric uncertainties the measured colors of these sources could be corrupted by the presence of the strong nebular background, and we performed an extensive set of artificial star photometry experiments to test this possibility. We found that nebular contamination can introduce some additional scatter to a star's measured J-H color and this can explain in part the J-H colors of $\sim$ 25% of the excess sources which are bluer than expected for late type sources (J-H $<$ 0.6). However, blueward J-H scatter can produce a false excess fraction ($\sim 10-20$%) only for the the faintest artificial stars, i.e., H = K = $\sim$ 16 mag. Further, we find that such nebular contamination never produces as large a dispersion of the H-K$_S$ colors as found in our observations of the candidate brown dwarfs, and we conclude that the observed infrared excesses are an intrinsic property of these objects.

4. DISCUSSION AND CONCLUSIONS

From analysis of their near-infrared colors, we find that $\sim$ 50% of the candidate brown dwarfs in the Trapezium cluster display significant near-infrared excess. This is similar to the behavior of the stellar population of this cluster and suggests the extreme youth of these low luminosity sources. This, in turn, provides independent confirmation of their membership in the cluster and their nature as bona fide substellar objects. As is the case for the more massive stellar members, the most likely explanation for the observed near-infrared excesses around the brown dwarfs in this cluster is the presence of circumstellar

[6] The predicted colors and magnitudes of the hydrogen burning limit for this distance/age combination are essentially identical to those for a younger assumed age (0.4 Myrs) but at a larger distance (470pc).

[7] and also ftp://ftp.ens-lyon.fr/pub/users/CRAL/fallard/

disks. Strong, independent support for the disk interpretation derives from the fact that we find 21 of the candidate brown dwarfs to be spatially coincident with optically identified HST "proplyds" (Bally et al. 2000; O'Dell & Wong 1996) which are known to be photo-evaporating circumstellar disks. We note that the proplyd brown dwarfs display a JHK excess fraction of 71%, while the brown dwarf candidates unassociated with known proplyds have a slightly lower excess fraction of 63%. The proplyd brown dwarfs also display bluer J-H colors than the remaining brown dwarf candidates and account for half the excess sources with J-H color < 0.6. Despite their relatively blue J-H colors, the proplyd nature of these sources affirms the hypothesis that the observed JHK infrared excess is intrinsic and a signature of the presence of a circumstellar disk.

The hypothesis that the observed near-IR excess is caused by circumstellar disks is further supported by observations of brown dwarf candidates in other clusters. Late-type brown dwarf candidates in the ρ Ophiuchi cluster were identified by their water vapor absorption features and display evidence for veiling in their infrared spectra as well as evidence for infrared excesses in their H-K/J-H color-color diagrams (Wilking et al. 1999; Cushing et al. 2000). ISO (6.7μm) observations reveal 4 brown dwarf candidates with mid-infrared excesses in Chamaeleon (Comerón et al. 2000). Luhman (1999) identified 7 brown dwarf candidates in the IC 348 cluster which, after de-reddening, fall to the right of the main-sequence reddening band but below the cTTS locus similar to the locus of brown dwarfs identified here. Luhman also identified strong Hα emission (W[Hα] > 10 Å) in a number of these sources and suggested that these are not simply passive circumstellar disks, but that these brown dwarfs are undergoing accretion. Finally, powerful evidence for accretion disks around very young brown dwarfs was found by Muzerolle et al. (2000) who identified an asymmetric Hα emission line profile for the M6 PMS object V410 Anon 13 in Taurus and successfully used magnetospheric accretion models to show that this brown dwarf candidate was indeed accreting but at a rate much lower than has been found in higher mass stars.

Compared to these other studies, our sample of Trapezium Cluster brown dwarfs is the first population that is sufficiently large to statistically estimate the frequency of substellar objects born with circumstellar disks. Indeed, there are now more brown dwarfs identified in the Trapezium cluster than are presently known in all other star forming regions combined. However, our estimate of the disk frequency from the JHK diagram could underestimate the true disk frequency for a number of reasons. First, JHK observations trace the innermost regions of disks and the particular disk geometry (inclination, presence of inner disk holes, etc.) can act to reduce the efficiency of detecting disks from JHK photometry, especially for late type sources (Hillenbrand et al. 1998; Lada & Adams 1992). For example, the $\sim$ 50% excess fraction we find for brown dwarfs is nearly identical to the excess fraction found in the JHK diagram of Lada et al. (2000) for objects in the cluster which are above the hydrogen burning limit. However, by employing 3μm photometry, these authors found a much higher, $\sim$ 85%, disk frequency even for the faintest members they detected. Indeed of the 10 M6+ sources shown in figure 1, 9 were detected at L band and although only one of these sources clearly displays H-K excess, 8 display K-L excess. Second, as a result of selecting candidate brown dwarfs at all reddenings we may have included reddened background field stars in the sample which would act to decrease the derived disk fraction. When we select candidates at low reddenings ($A_V \leq 5$ relative to the isochrone in the figure 1a) to exclude background field stars, we find 77% (57/74) of this sample display infrared excess. Further, this sample is an extinction limited sample which is complete at all masses in our selected range and therefore is likely representative of the population as a whole.

We conclude from our current study and from the findings of Lada et al. (2000) that circumstellar disks are present around a high fraction of Trapezium Cluster members *across the entire mass spectrum*. This implies that brown dwarfs and higher mass stars form via a similar mechanism, e.g., from individual contracting fragments of the parental molecular cloud which, via conservation of angular momentum, form a central star accompanied by a circumstellar disk (Shu, Adams, & Lizano 1987). Low & Lynden-Bell (1976) showed that within the conditions of molecular clouds, the minimum Jeans mass for a cloud fragment could be as small as 0.007 $M_{\odot}$, well below the mass necessary to create the Trapezium brown dwarfs. The free-floating nature of these brown dwarfs rules out their formation as companions in a circumstellar disk unless the sources were ejected. But models of dynamical ejection of these objects from hierarchical systems predict that any circumstellar material will be disrupted during the ejection process and that circumstellar disks should be rare among ejected brown dwarfs (e.g., Reipurth & Clarke 2001). Thus our results seem to implicate a formation mechanism for brown dwarfs in which such objects are formed with circumstellar disks from individual proto-*sub*stellar cores. Consequently, even sub-stellar objects may be capable of forming with systems of planetary companions.

Confirmation of our hypothesis that a substantial fraction of the brown dwarfs in the Trapezium are surrounded by circumstellar disks requires additional data. Deep 3μm ground-based observations such as those used by Lada et al. (2000) are necessary to permit a more accurate measurement of the excess fraction for the brown dwarf population. Longer wavelength infrared observations, such as those that will be possible with SIRTF, would enable the construction of more complete SEDs for these sources which could then be compared directly to theoretical disk predictions. Estimates of the masses of the disks would have interesting implications for the possibility of forming planetary companions around brown dwarfs. Finally, high resolution spectra of these objects would enable searches for accretion indicators, such as Hα emission, veiling, etc., which could yield accretion rates and information about the growth and early evolution of these interesting objects.

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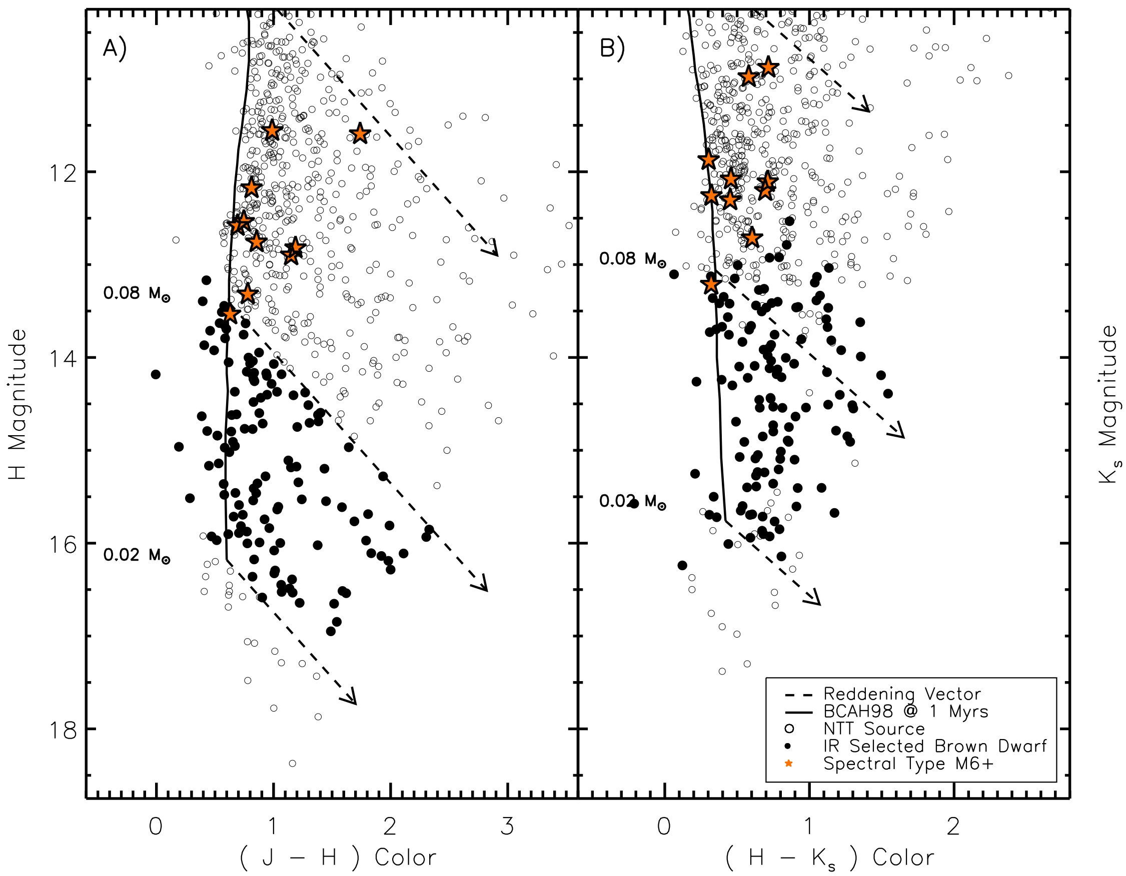

FIG. 1.— Candidate Brown Dwarfs from the Trapezium Cluster Infrared Color-Magnitude Diagrams. Only sources having NTT observations and JH and K_S magnitudes are shown. Trapezium sources are compared to the location of the 1 Myr (at 400pc) isochrone from the BCAH98 model atmospheres. Candidate brown dwarfs (filled circles) were selected by their H band luminosities (and colors) and are marked in both color-magnitude diagrams. Reddening vectors for 1, 0.08 and 0.02 $M_\odot$ objects are drawn at visual extinctions of 20, 20 and 10 magnitudes, respectively. Stars with spectral types $\geq$ M6 are identified as filled stars. a) J-H/H color-magnitude diagram. b) H-K_S/K_S color-magnitude diagram.

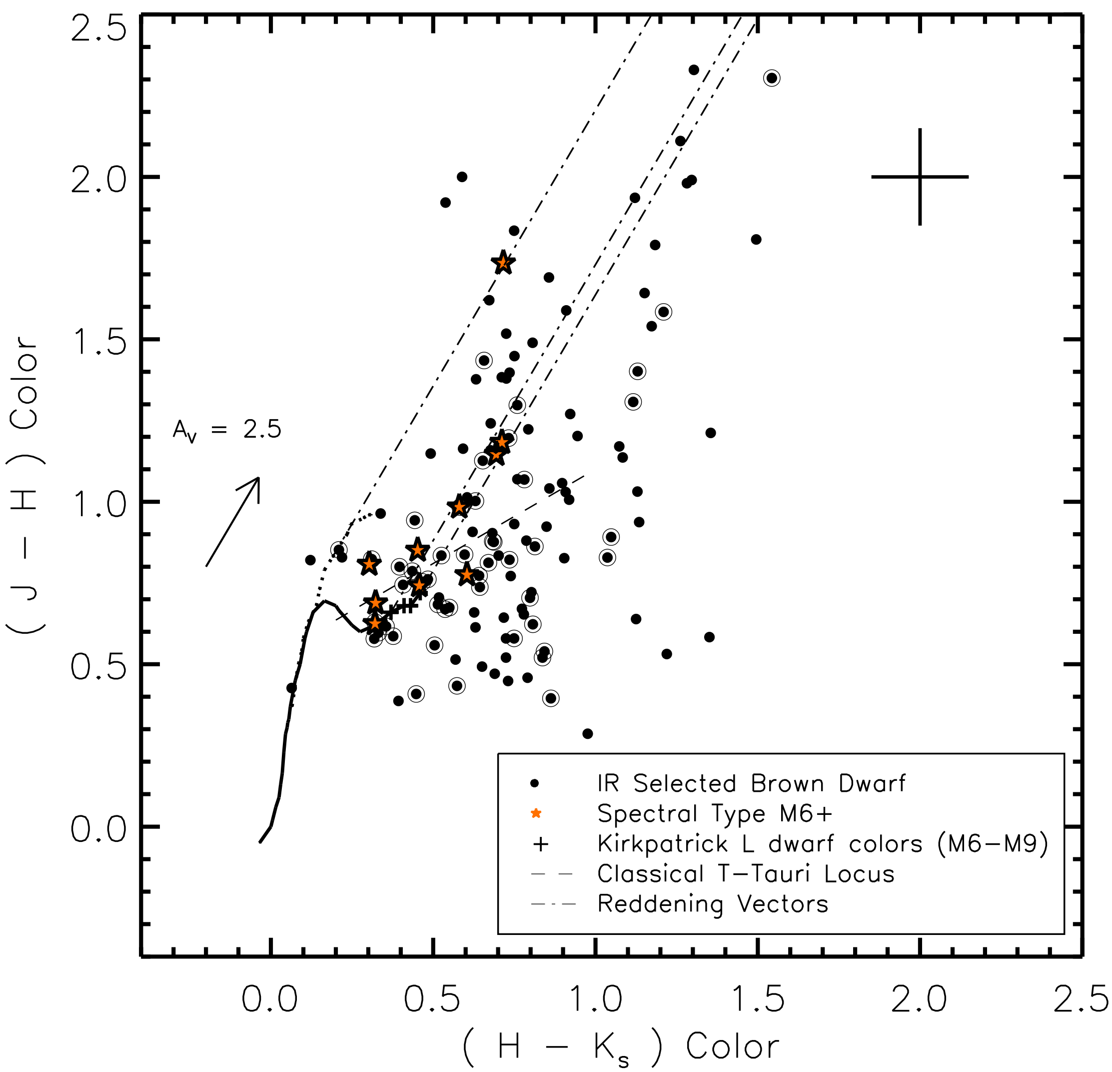

FIG. 2.— H-K_S/J-H color-color diagram for the 109 sources with NTT JHK_S magnitudes and which fall into brown dwarf regime of Fig 1a. The candidate brown dwarfs are compared to the intrinsic colors of giants and A0-M6 dwarfs from Bessell & Brett (1988), the late M (M6 - M9) color sequence from Kirkpatrick et al. (2000) and the Classical T-Tauri locus from Meyer, Calvet, & Hillenbrand (1997). Appropriate reddening vectors (Cohen et al. 1981) are drawn for giants, for M6 stars and for M9 stars. Colors of Trapezium sources with very late (M6+) spectral types are shown as stars. Circled sources have color errors of less than 10% and the size of 15% uncertainties in color are illustrated at the upper right.